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Review

Soils: their implications to human health

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Abstract

This paper reviews how the health of humans is affected by the world's soils, an association that to date has been under appreciated and under reported. Soils significantly influence a variety of functions (e.g. as a plant growth medium; its importance on the cycling of water; as a foundation for buildings) that sustains the human population. Through ingestion (either deliberate or involuntary), inhalation and dermal absorption, the mineral, chemical and biological components of soils can either be directly beneficial or detrimental to human health. Specific examples include: geohelminth infection and the supply of mineral nutrients and potentially harmful elements (PHEs) via soil ingestion; cancers caused by the inhalation of fibrous minerals or Rn gas derived from the radioactive decay of U and Th in soil minerals; and tetanus, hookworm disease and podoconiosis caused by skin contact and dermal absorption of appropriate soil constituents. Human health can also be influenced in more indirect ways as soils interact with the atmosphere, biosphere and hydrosphere. Examples include: the volatilisation of persistent organic pollutants (POPs) from soils and their subsequent global redistribution that has health implications to the Aboriginal people of the Arctic; the frequent detrimental chemical and biological quality of drinking and recreational waters that are influenced by processes of soil erosion, surface runoff, interflow and leaching; and the transfer of mineral nutrients and PHEs from soils into the plants and animals that constitute the human food chain. The scale and magnitude of soil/health interactions are variable, but at times a considerable number of people can be affected as demonstrated by the extent of hookworm infection or the number of people at risk because they live in an I-deficient environment. Nevertheless, it can often be difficult to establish definite links between soils and human health. This, together with the emergence of new risks, knowledge, or discoveries, means that there is considerable scope for research in the future. Such investigations should involve a multidisciplinary approach that both acquires knowledge and ensures its dissemination to people in an understandable way. This requires an infrastructure and finance that governments need to be responsive to.

Keywords: Dermal absorption; Environmental geochemistry; Geophagy; Hookworm disease; Infectious diseases; Mesothelioma; Persistent organic pollutants; Podoconiosis; Radon; Soil inhalation; Soil ingestion; Water quality

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1. Introduction

Soil has always been important to humans and their health, providing a resource that can be used for shelter and food production. As good examples of the former, the ancient loess villages excavated into the sides of ravines at Yang Shao Tsun in China or the contemporary dwellings cut into sun-baked clays near Matmata in southern Tunisia may be cited (Pitty, 1979). More widely, soil materials continue to be daubed on the sides of wooden frameworks and are exploited for the manufacture of bricks. With sophisticated buildings, the soil on which their foundations rest is important. At times, such soils are prone to shrinking and swelling, collapse and liquefaction, which pose a hazard to the integrity of the buildings if not the humans occupying them (McCall et al., 1996).

The link between a rising world population and the ability of the soil to support an increasing food supply has been of concern since Thomas Malthus wrote his first famous essay in 1798. There has always been an important association between soils and agriculture, with Stone Age farmers recognised as the first soil surveyors (Vink, 1963). At times, the over-exploitation of soils attributable to a desire to increase food production led to its serious degradation, failure to produce sufficient food for people and the collapse of societies (Hyams, 1976). For example, speculation on the decline of the Mesopotamian civilisations has been attributed in part to soil degradation brought about by erosion and salinisation. The collapse of the Maya Empire in approximately A.D. 600 may have been due to soil nutrient exhaustion, erosion and resulting malnutrition (Olson, 1981). Human population growth and the maintenance of an adequate food supply are certainly ancient problems but with a global population, that may increase to a predicted 10 billion before it stabilises, the challenge for a solution continues. Although soil is not the only factor affecting world food supply, this natural resource is clearly important in overcoming one of humankind's most complex challenges. Food insecurity occurs throughout the developing world, but is most acute in sub-Saharan Africa which has the highest rate of land degradation, and where per capita food production continues to decrease. Consequently, Sanchez et al. (1997) conclude that although the Malthusian nightmare is unrealistic at the global scale, it could become a reality in Africa. World food production is considered likely to continue to rise as demand increases in the short to medium term, but the future management and conservation of the world's soils is of great importance. A very recent study reports that long-term food productivity is threatened by soil degradation, which is now severe enough to reduce yields on approximately 16% of agricultural land, especially cropland in Africa and Central America and pastures in Africa (Wood et al., 2000).

Soils have an impact on human health in many other ways, although comprehensive reviews on this topic are limited (Oliver, 1997), suggesting that the subject has been undervalued. The purpose of this communication is to document the relative importance and variety of links that exist between soils and human health, and in this respect to stress a significance of soils to humans that, to date, few people fully appreciate. In addition, those humans whose health is especially affected by soils: are recognised; some measures to improve their health are discussed; and some key priorities for the future are identified. The ingestion, inhalation, or dermal absorption of soil constituents can have a direct impact on human health, but soils can also indirectly affect the health of people by influencing properties of the atmosphere, hydrosphere and biosphere. The direct links between soils and human health are initially considered in this review, followed by an appraisal of the more indirect associations.

2. Soils and human health: direct links

2.1. Ingestion

The ingestion of soil occurs either involuntarily or deliberately. For the former, all members of an exposed population will ingest at least small quantities of soil (Ferguson and Marsh, 1993). One reason for this is that any soil adhering to the skin of fingers may be inadvertently ingested by so-called hand-to-mouth activity. Young children are especially vulnerable to this, and furthermore they have a predilection for eating non-food items such as soil (Hawley, 1985). Any outdoor activity is likely to result in an increase in ingestion. Thus, in Dutch children aged 1–5 years, the rates of soil ingestion were increased during dry periods when they spent more time outdoors (van Wijnen et al., 1990). Soil is also an important constituent of house dust that provides another source of exposure (Fergusson et al., 1986), while certain foods, especially in the developing countries, are often contaminated with soil particles that will be consumed if not properly washed (Hallberg and Björn-Rasmussen, 1981). The rates of soil ingestion are estimated using tracer elements such as Al, Si and Ti, or the acid insoluble residue (AIR) content of the soil. To date most studies have investigated children because of their vulnerability to soil ingestion (e.g. Binder et al., 1986; Clausing et al., 1987; Davis et al., 1990; LaGoy, 1987). Some attempt has also been made to evaluate soil ingestion by adults (Calabrese et al., 1990), with Stanek et al. (1997) reporting an average adult soil ingestion rate of 10 mg d^{-1}. Stanek et al. (1990) noted that the median is the most robust and best estimate of soil ingestion since it is insensitive to the various assumptions made in forming estimates. Depending on the tracer element used, these authors reported a median soil intake by 64 children from Massachusetts aged 1–4 years that ranged from 9 to 96 mg d^{-1} [though Calabrese et al. (1989) noted from the same data that the three most reliable tracers, Al, Si and Y, reveal a range in median values of 9–40 mg d^{-1}]. The estimates of soil ingestion in the literature however are highly variable and of questionable reliability (Calabrese and Stanek, 1994). These authors further concluded that it could be assumed that children 6–12 years of age ingest 25% of the amount of soil consumed by a 1–6-year-old-child. Those over 12 years of age can be assumed to ingest 10% of soil relative to a 1–6-year-old-child (based on diminished hand-to-mouth activity and other maturational and social factors).

Young children normally explore the environment by mouthing until at least 12–18 months of age, and most authors consider soil ingestion as abnormal if undertaken deliberately beyond the 18–24-month period. The term pica can be applied to any form of abnormal ingestion which involves substances that are not normally regarded as edible, but specifically the terms geophagy or geophagia relate to the deliberate ingestion of soil. For many people, especially those of the developed countries, geophagy is difficult to comprehend. Even among those of the academic fraternity, words such as bizarre, filthy, degrading, morbid, odd and curious have been applied to geophagists who on occasions are referred to as 'dirt eaters' (e.g. Dickens and Ford, 1942). Yet literature reviews undertaken on this practice clearly show its antiquity and worldwide distribution (Anell and Lagercrantz, 1958; Cooper, 1957; Laufer, 1930). Such reviews indicate that geophagy is not limited to any particular age group, race, sex, geographic region, or time period. Today, however, deliberate soil ingestion is especially associated with certain geographic areas [e.g. the tropics; Abrahams and Parsons (1996)] and people (e.g. those of low socio-economic status; rural black women of the American South; pregnant women; children). The reasons why such people indulge in eating soil are manifold, and whilst there is some evidence to suggest that geophagy has declined in some societies (Frate, 1984), there is sufficient information to indicate that in others the practice is common and probably more prevalent than previously estimated. For example, of 285 school children aged 5–18 years in western Kenya, 73% indulged in geophagy (Geissler et al., 1997). These authors reported the median soil intake as 28 g d^{-1} (range = 8–108 g d^{-1}), whilst O'Rourke et al. (1967) noted a mean of 50 g d^{-1} (range = 2–650 g d^{-1}) for 62 pregnant women in Georgia (USA). Qualitative estimates [e.g. 'a shoe box full a week' (Abbey and Lombard (1973)] also indicate the substantial quantities of soil that can be consumed by geophagists. Frequently, such people develop a craving and uncontrollable urge for eating soil, a condition that may be termed geomania (Halsted, 1968).

The medical implications of soil ingestion are manifold. This is especially the case for geophagists because of the large amounts of soil that can be consumed. An excessive intake of soil can lead to the death of an individual. Black slaves in the New World used to commit suicide by undertaking geophagy due to a firm belief that after death they would return spiritually to their native home. It is reported that in 1687, approximately 50% of deaths among the slaves in Jamaica was attributable to this problem (McNeill, 1987; cited in Robinson et al., 1990). Very harsh measures including the use of masks, iron gags and the chaining to floors, were introduced to try and control geophagy, so grave was the outcome of this practice.

One consequence of soil ingestion is that the amounts and balance of mineral nutrients within the individual will be affected. According to Hendricks (cited by Cooper, 1957), clays entering the alimentary tract will first encounter the acidity of the stomach giving up the elements that they hold by cation exchange. In addition, iron hydroxides will undergo some solubility. Consequently, important amounts of mineral nutrients such as Ca, Cu, Fe, Mn, Mg and Zn can be supplied directly to geophagists via ingested soil (Johns and Duquette, 1991). It has been suggested that geophagy represents a craving generated by a nutritional deficiency. For example, Shuttleworth et al. (1961) report on a case of geophagy by an infant who then ceased to eat soil following Co therapy. But a physiological cause of geophagy remains a controversial issue, with Feldman (1986) considering that there are no consistent and well-controlled data to support such a hypothesis. Nevertheless, soil ingestion provides for a direct soil–human geochemical pathway (Abrahams, 1999), and irrespective of whether soils are being deliberately consumed for their mineral nutrients, ingested soils have the potential to supply important elements such as Fe to an individual (Abrahams, 1997; Smith et al., 2000a). Sometimes too much may be supplied, and toxicity can result. Gelfand et al. (1975) report on five cases of life-threatening hyperkalaemia caused by the absorption of large amounts of K from soils enriched in this element.

In addition to being a potential nutrient provider, soil ingestion in association with other factors such as diet and parasite infection may lead to a deficiency problem. Iron deficiency anaemia resulting from impaired iron absorption from the gastrointestinal tract following soil ingestion has been widely reported (Tevetoglu, 1956; Minnich et al., 1968; Mokhobo, 1986), although conversely iron deficiency may be the cause of geophagy (Lanzkowsky, 1959). Hypokalaemia and hypozincaemia have also been associated with geophagy (Cheek et al., 1981; Severance et al., 1988). For example, growth retardation and delayed puberty is associated with zinc deficiency among geophagists in Turkey (Çavdar et al., 1980). A poor diet contributes to this, but geophagy can be considered as an accelerating factor of zinc deficiency in people who have already a low Zn intake. In such cases, oral Zn treatment improves linear growth and sexual maturation in affected individuals.

In terms of toxicity of elements via soil ingestion, most concern to date has been centred on Pb. In the mineralised/mining province of Derbyshire (England), Barltrop et al. (1974) found that Pb-contaminated soils may lead to increased absorption of the element in local village children aged 2–3 years, but to an extent that is unlikely to be of biological significance. Furthermore, although soil ingestion was prevalent to an unexpected degree, the practice appeared to be a relatively unimportant source of Pb for children. Subsequent research in the same geographical area indicated that elevated levels of Pb are transferred to children by the soil–dust–hand–mouth pathway, but this is not reflected in the blood Pb concentrations which are within normal UK ranges. The reason for this appears to be the chemical weathering of primary galena [PbS] to pyromorphite [$Pb_5(PO_4)_3Cl$], a stable soil-Pb mineral of extremely low solubility that may contribute to a low human bioavailability in these soils (Cotter-Howells and Thornton, 1991). Elsewhere, the potential hazard of Pb-contaminated soil to geophagists has been emphasised not only in children (Shellshear et al., 1975), but also in adults (Wedeen et al., 1978). Children are of most concern, however, with Pb as a neurotoxin being especially harmful to the developing brains and nervous systems of young people. In the US, Pb poisoning is a very important health issue that has been described as the silent epidemic, with medical, learning and social costs having broad and long-term implications. While there has been a substantial decline in blood Pb concentrations during the last decade (attributed to removal from petrol, as well as reducing Pb in the food canning process), currently there are approximately 900 000 children under 6 years old in the US that have at least 10 μg Pb dl^{-1} in their blood. This is a level high enough to adversely affect intelligence, behaviour and development [CDC, cited in Mielke et al. (1999)]. Urban soils in large US cities, especially those found in the central districts where the highway networks have concentrated traffic, are a giant reservoir of Pb (and other elements such as Cd and Zn) because of pollutants such as leaded petrol and paint (Mielke, 1999). Consequently many children in such areas face a significant risk of Pb poisoning from the deliberate or otherwise ingestion of soil from their local yards, school playgrounds (Higgs et al., 1999) and, to a lesser extent, in the open spaces around their homes. For this reason, it is important that soil ingestion be considered in any risk assessments involving not only Pb, but also other potentially harmful elements (PHEs; e.g. As) and organic contaminants such as dioxins (Gough, 1991; Lee and Kissel, 1995; Lee et al., 1995). The importance of urban soils is also evident, though to date their significance has been undervalued. Consequently, while many investigations have studied metals in these soils, research on other constituents such as pesticides and hydrocarbons remains limited (Thornton, 1991).

Soil ingestion can be detected by dental inspection [which can reveal excessive tooth wear (Abbey and Lombard, 1973)], and by radiological examination of the abdomen that will reveal opaque masses of soil in the colon (Mengel and Carter, 1964). Constipation; the reduction of the power of absorption of food materials by the body; severe abdominal pain; and obstruction and perforation of the colon may result following the internal accumulation of soil (Amerson and Jones, 1967; Bateson and Lebroy, 1978; Solien, 1954). In pregnant women, this can lead to dysfunctional labour and maternal death (Horner et al., 1991; Key et al., 1982).

Along with the ingestion of soil, the eggs of parasitic worms (geohelminths) can also be consumed. Ascariasis (characterised by abdominal pain and nausea with disturbed functioning of the alimentary tract) and trichiuriasis are caused by the ingestion of *Ascaris lumbricoides* and *Trichuris trichiura* eggs, respectively. Work undertaken in Jamaica (Wong et al., 1991) and Kenya (Geissler et al., 1998) provided a quantitative estimate of the level of exposure to intestinal *A. lumbricoides* and *T. trichiura* infection experienced by geophagous children. In addition, soil ingestion can also lead to toxocariasis infection through the consumption of *Toxocara canis* (the common dog roundworm) or *T. cati* (cat roundworm) eggs. Following ingestion, the larvae are carried by the bloodstream into different tissues and organs of the human host, causing a clinical syndrome of visceral larva migrans (VLM), characterised by inflammation and eosinophilic granulomas. The other common human syndrome is ocular larva migrans (OLM) induced by larvae penetrating into the eye. The clinical picture varies from a solitary retinal granuloma to severe endophthalmitis. The prevalence of toxocaral disease appears to be greater than previously thought (Caucanas et al., 1988), and in the Slovak Republic subclinical toxocarosis was estimated at 13.65% (Havasiová et al., 1993). Perhaps this should not be surprising bearing in mind that environmental contamination can be widespread; in Italy, *T. canis* eggs were found in 30% of soil samples (Genchi, 1976; cited in Arpino et al., 1990). Whilst the toxocaral disease can manifest with few and mild symptoms, the greatest burden falls on young children most likely because of geophagy (Havasiová et al., 1993; Rée et al., 1982).

2.2. Inhalation

Wagner (1980) notes that the bulk of mineral dusts that are inhaled by humans are trapped and subsequently ingested, passing through the gastrointestinal tract. Nevertheless, some inhaled mineral dusts are retained in the lungs where they can cause damage to humans via irritation with the production of bronchitis, scarring with the production of fibrosis (pneumoconiosis) and cancers (Gilson, 1977). The reaction of the lungs to mineral dusts depends on the dosage and nature of the dust inhaled (Wagner, 1980). Because mineral dusts are ubiquitous in the environment due to widespread human activity (e.g. soil cultivation, quarrying), and because of dissemination of particles from natural sources, all humans have a small amount of minerals in their lungs. The amount of dust in this organ needed to cause disease is considerable, and industrial exposure (e.g. coal worker's pneumoconiosis; silicosis due to excessive exposure to quartz dust) remains the main concern. However, Brady and Weil (1999) note the potential importance of airborne clay-sized particles (so-called 'fugitive dust') which result because of soil (wind) erosion. With subsequent inhalation and lodgement in the alveoli of the lungs, inflammation of this organ can result. Furthermore, airborne particles coated with toxic substances such as sulfuric or nitric acid will cause further lung damage. Consequently, Brady and Weil (1999) state that long-term epidemiological studies undertaken in the U.S.A. have suggested that the number of deaths resulting from people inhaling fine fugitive dust may exceed the number of deaths from car highway accidents.

Fibrous serpentine and amphibole minerals, commercially called asbestos, are more dangerous than so-called isometric (i.e. equidimensional) dust particles (Elmes, 1980). Lower quantities of the former minerals need to be retained in the lungs to cause diseases that include two cancers (primary lung cancer and mesothelioma of the pleura or peritoneum. Note, isometric dusts, unless radioactive or contaminated with chemical carcinogens, do not cause cancer). As with isometric dusts, occupational groups of people are most at risk to asbestos, and the World Health Organisation (1986) considered that, for the general population, the risks of cancer attributable to asbestos could not be quantified reliably, and were probably undetectably low. However, more recent research in north-east Corsica has indicated that environmental exposure to airborne chrysotile and especially tremolite fibres cause an elevated incidence of pleural plaques (scarring) and mesothelioma (Rey et al., 1993a,b). On the basis of the results obtained from this work, the risk is considered to be 10 cases of mesothelioma per 100 000 inhabitants per year. Endemic malignant pleural mesothelioma (MPM) has also been reported from rural Turkey where inhabitants of certain villages are exposed to soil dusts containing tremolite and a fibrous zeolite, erionite. The lesions produced by the two minerals are different (Erzen et al., 1991), and erionite may be the most carcinogenic (Bish and Chipera, 1991). Selcuk et al. (1992) report that the median survival time after diagnosis was 13.52 months for erionite-associated MPM, and 21–56 months for asbestos-associated MPM.

The inhalation of soil mineral material has caused human health problems elsewhere. Wagner (1980) reports the presence of coarse tremolite in the soil of some areas of the Balkans where large calcified pleural plagues have been recorded among agricultural workers. However, these cause no disability. Similar findings have been recorded in other countries such as Finland, attributable to dust containing tremolite or other asbestiform minerals perhaps entrained into the atmosphere through cultivation (Gilson, 1977). During the last three decades, poorly planned irrigation in Central Asia has brought about the desiccation of the Aral Sea and the desertification of the former sea bed and adjacent territories (Saiko, 1998). Soviet cosmonauts first spotted major storms of dust and salt in 1975, and by the 1980s the storms carried between 90 and 140 million tons of salt and sand per year from more than 28 000 square kilometres of exposed seabed. The toxic 'salt rains' are deposited not just on the soil, but in the lungs of those who work on the land, contributing to the poor health problems of the local population (Feshbach and Friendly, 1992).

The above ground atmosphere is an important source of Rn to humans (Fig. 1), though the gas is derived through the radioactive decay of ^{238}U and ^{232}Th in rock and soil minerals. Inhalation of the gaseous, radioactive isotopes ^{222}Rn and ^{220}Rn is of concern because epidemiologists suspect that the inhaled Rn and the solid daughter products in the lungs lead to, or are an important factor contributing to, lung cancer. Radon may also be a causative factor in the induction of myeloid leukaemia and other cancers (Henshaw et al., 1990). ^{222}Rn and ^{220}Rn are the only gaseous decay products in the ^{238}U and ^{232}Th series, respectively. As such, the Rn is potentially mobile and can diffuse through rock and soil to escape into the above ground atmosphere. The amount of escaping Rn varies enormously (Bowie and Bowie, 1991; Varley and Flowers, 1993; Jones, 1995), depending on the geology (e.g. U content and its chemical form, degree of jointing/faulting), soil characteristics (e.g. permeability, moisture content) and

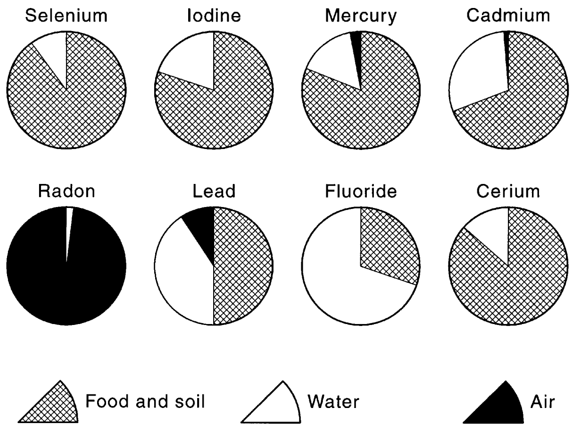

Fig. 1. The relative importance of various exposure routes for some essential elements and PHEs (Plant et al., 2000). The importance of the soil is greater than these diagrams initially suggest. For example people receive most of their F from water that in turn comes from soil (as well as rocks), whilst atmospheric Rn is derived from radioactive isotopes of U and Th in soil (and rock) minerals.

climatic variables (e.g. temperature, humidity). The much shorter half-life of ^{220}Rn (55 s), compared to that of ^{222}Rn (3.82 d), makes diffusion of the former into the above ground air less probable (Steinnes, 1990). Consequently, ^{222}Rn is of most concern, and much of this gas can escape directly into outdoor air where the typically very small background concentrations yield insignificant amounts of the annual effective dose of ionizing radiation to humans (Clarke and Southwood, 1989). Sometimes local soils can contribute to elevated outdoor ^{222}Rn concentrations, and such exposure needs to be included in epidemiologic studies. This was the conclusion of Steck et al. (1999), who found unusually high annual average Rn outdoor concentrations in parts of central North America.

While the gas can disperse quickly in open air, Rn can enter and accumulate in dwellings as a component of soil gas drawn from the soil by mass flow driven by the pressure difference between the house and soil beneath (Sharman, 1992). According to Baird (1998), most Rn that seeps into homes comes from the top metre of soil below and around the foundations. This author states that the ^{222}Rn itself does not pose much of the danger to humans; instead the daughter isotopes, in particular ^{214}Po and ^{218}Po, adhere to dust particles which are then inhaled to cause radiation damage to the bronchial cells near which the dust particles reside. It was not until the early 1970s that this potential hazard from the inhalation of Rn gas and the daughter progeny in the domestic environment was first identified. The extent of the problem will vary globally, and in equatorial areas where domestic conditions are usually different, the indoor level of ^{222}Rn and its daughters is likely to be considerably lower than in the northern temperate regions. In the latter areas, the radon problem can be evaluated by making reference to the United Kingdom. Here, surveys have shown that 100 000 houses built on certain types of ground mostly in Cornwall and Devon, and in some parts of Derbyshire, Northamptonshire, Somerset, Grampian and the Highlands of Scotland, are more likely to have high indoor Rn levels. South-west England (i.e. Cornwall and Devon) is particularly affected, containing 53% of UK homes estimated to contain a concentration of ^{222}Rn above the Action Level of 200 Bq m^{-3}. The granites found within this region have a relatively high U content, and are suitably jointed and fractured to generate a high Rn emanation rate. Varley and Flowers (1998) showed that soil gas concentrations over the granites were twice that found in soils above other rocks and, as expected, homes located in granite regions had the highest indoor Rn levels. Until recently, there was no direct evidence that the Rn levels occurring in domestic houses are a cause of lung cancer, but it was estimated that residential Rn is responsible for approximately 1 in 20 cases of lung cancer deaths in the UK (approx. 2000 per year). The first direct evidence for the link between residential Rn and lung cancer has been published relatively recently (though not without some controversy, see Miles et al., 1999), and agrees with these figures (Darby et al., 1998). Working in south-west England, these authors found that the relative risk of lung cancer increased by 8% per 100 Bq m^{-3} increase in the residential Rn concentration.

Inhalation of the biotic component of soils may also pose certain risks to humans. It has been reported that the global atmospheric redistribution of African 'dusts' containing bacteria, viruses and fungi from deserts may have contributed to dramatic increases in respiratory diseases such as asthma over the past 20 years (Pearce, 1999a). The same report claims that the soil fungus *Aspergillus* is a major killer of people with AIDS, causing lung infections when the immune system is depressed. Werner et al. (1972) describe an epidemic of coccidioidomycosis among a group of archaeological students who were digging some Indian ruins in northern California. This is an infectious disease, also called desert fever, desert rheumatism, or valley fever, caused by inhalation of spores of the fungus *Coccidioides immitis* (Weller, 1989). Typically 60% of infected persons show no symptoms, whilst the rest develop a flu-like illness that can last for a month, and tiredness that can sometimes last for longer than a few weeks (ASTDHPPHE, 2001). A small percentage of infected persons ($<1\%$) can develop disease that spreads outside the lungs to the brain, bone and skin. Of the 103 members of the archaeological excavation in California, at least 61 developed symptoms. Arthrospores typical of *C. immitis* were observed in cultures of a soil sample taken from a rodent burrow, leading Werner et al. (1972) to unrealistically recommend that archaeological digging should not be done directly into rodent burrows. The fungus grows in hot, dry areas, especially in the south-western United States, Mexico and parts of Central and South America. In the United States, an estimated 50 000 to 100 000 persons develop symptoms of coccidioidomycosis each year (ASTDHPPHE, 2001). The disease is increasing because of the growing number of people who are moving to affected areas such as Arizona, and because of increases in the number of persons with weakened immune systems that are at greater risk of infection. Recent natural disasters in California (drought and earthquakes, both of which lead to increased dust in the atmosphere) have also triggered a rise in cases of this disease. This is of concern, since without treatment coccidioidomycosis can lead to severe pneumonia, meningitis and even death. Fortunately, the disease can usually be treated with fungus-killing medicines.

Archaeologists, farmers, construction workers and military personnel constitute groups of people who, because of their occupation, are particularly at risk from infection from a number of soil organisms. However, none of the organisms that caused mass death in the past (e.g. plague, typhoid, tuberculosis, anthrax and smallpox) are likely to survive long in buried human or other animal remains (Healing et al., 1995). Despite this, at times caution may still be needed. For example, the world was declared free of smallpox in 1979, and the virus is unlikely to remain viable for long following earth burial. However, in exceptionally cool, dry conditions (the ultimate example being burials in permafrost) survival of the virus may be significantly prolonged (Meers, 1985).

2.3. Skin contact and dermal absorption

Tetanus is potentially the most likely of the infectious diseases to affect people such as archaeologists who come into contact with the soil, and it has been suggested that no one who has not been immunised against this disease should be allowed to undertake an archaeological dig (Waldron, 1985). This acute and often fatal infectious disease, also known as lockjaw or trismus, is characterised by muscular rigidity with superimposed agonising contractions (Salisbury and Begg, 1996). The clinical manifestations of tetanus are due to a toxin produced by the growing spores of the anaerobic micro-organism *Clostridium tetani*. This bacillus, found in the surface layers of soil (and in human and animal excreta), is particularly abundant in cultivated and manured fields, especially in the tropics. However, where such soil is at high altitude (e.g. Ladakh, Lesotho) the incidence of tetanus is markedly lower. Infection is usually caused by contamination of wounds, burns, or lacerations with spore-bearing soil (in a similar way another species of bacteria, *Clostridium perfringens*, can enter wounds causing gas gangrene).

Tetanus is a world-wide disease, attacking not only humans but also virtually all warm blooded animals. People of all ages may be affected, although the greatest incidence is in boys under 15, in view of their greater exposure to traumatic injuries. There are great differences in the natural incidence and severity of tetanus apart from the effect of immunisation programmes (Sanders, 1996). Social environment, season and climate as well as soil all contribute to variations in the disease, and occupations may be a predisposing factor, as in the case of soldiers and farmers. More tetanus can be expected in rural areas where manual labour is intense. Interestingly, people living in such communities probably ingest regular quantities of the bacillus and natural immunity develops through mouth and gut absorption (Sanders, 1996).

Hookworm disease, characterised by various clinical features with anaemia being the classical manifestation of the disease, is also caused by skin contact with soil. The disease has been effectively reviewed in a series of papers edited by Gilles and Ball (1991), wherein hookworm infection (defined as the presence of adult hookworms in the small intestine) has been called 'one of the greatest silent scourges of mankind'. There are two major species of anthropophilic hookworms, *Ancylostoma duodenale* and *Necator americanus*. A third species, *Ancylostoma ceylanicum,* also matures in humans, but occurs usually only rarely and at low densities. Fig. 2 describes the life history of these hookworms, and shows how infection occurs by skin penetration. Whilst in the soil, the survival of hookworm larvae is favoured in a damp, sandy, or friable environment with decaying vegetation and a temperature range of 24–32 °C. However, *A. duodenale* and *A. ceylanicum* infection can occur via the oral ingestion of contaminated food and, presumably, soil. The prevalence of hookworm infection is high in many parts of the rural tropics, with peak prevalence occurring in young adult life. Hookworm organisms are parasites in nearly one in four of the human race, and this is likely to continue for many years to come.

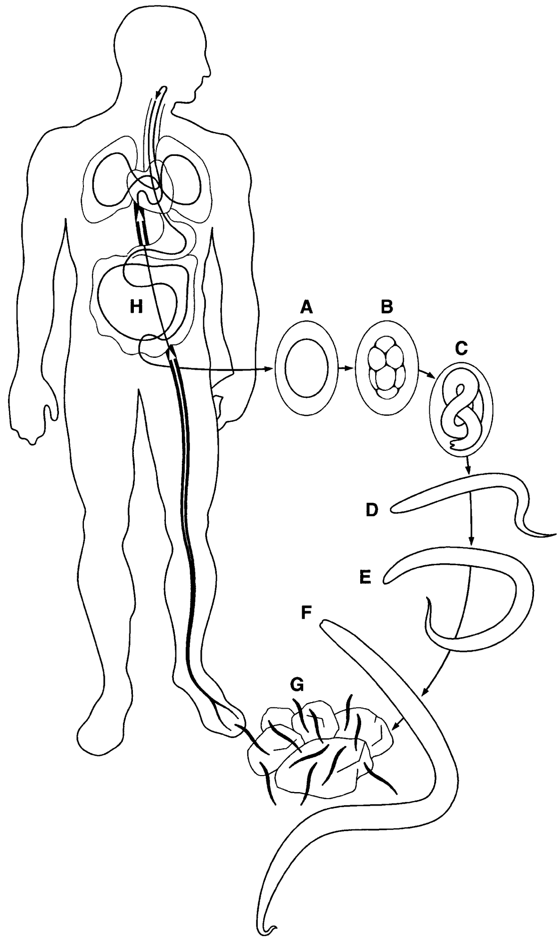

Fig. 2. Life history of the hookworm. Eggs (A) are deposited in the intestinal lumen and pass from the host in the faeces. Following embryonation and larval development (B–F), the third stage larva (F) can migrate out of the soil to accumulate on soil surface particles (G). Skin penetration infects the host, with the infective larvae then migrating to the lungs via the circulation. Migration to the intestine (H) then occurs where fourth stage larvae and adult worms establish, feeding on intestinal mucosa and the host's blood. Note that *Ancylostoma duodenale* and *A. ceylanicum* can also be infective orally, then developing in the intestines without further migration (adapted from Schad, 1991).

Non-filarial endemic elephantiasis, a disease renamed by Price (1988) as podoconiosis, is characterised by an asymmetrical swelling of the feet and lower limbs. The disease has curable pre-elephantiasic and incurable elephantiasic stages, but once established podoconiosis persists until death from some other cause. The Persian physician El Razi first described the disease 1000 years ago, but over 40 years of investigations by Price in the 20th century led to its virtual rediscovery. Podoconiosis results from blockage of the lymph nodes by soil. Histopathological examination of these nodes shows them to contain birefringent minerals which, by micro analysis, have been identified as sub-micron particles of kaolinite and small amounts of quartz, haematite, goethite and gibbsite.

Price (1990) records the geographical distribution of podoconiosis, stating that the disease is especially found in Africa, the Americas (for example, being present to a varying degree in all Central American countries) and north-west India. Single reports from other parts of the world, for example São Tomé and Príncipe in the Gulf of Guinea (Ruiz et al., 1994), suggest that the extent and rate of prevalence is still largely unknown. Recent research has univocally documented podoconiosis for the first time in Uganda, precisely indicating a geographical location where the condition prevails (the Mt Elgon area), and suggesting that other parts of Uganda with similar environmental conditions may be endemic for the disease (Onapa et al., 2001). In the highland areas of Africa, a prevalence rate of up to 70 per 1000 adults can be found. Here, barefooted agriculturalists are especially vulnerable, with podoconiosis being less common in pastoral areas. Superimposing the prevalence data for the disease on a geological map of Africa reveals a correlation between alkali basalt rocks and podoconiosis. Weathering of these rocks produces fine reddish-brown soils containing the colloid-sized particles that are capable of penetrating unbroken skin. Soils from such endemic upland areas contain more particles of <5-μm size than found in lowland non-endemic areas (Price and Plant, 1990). However, apart from the increased proportions of these particles in soils of the endemic areas it is unclear, bearing in mind that constituents like kaolinite and quartz are common soil minerals, why they should become toxic. Fyfe and Price (1985) injected crystalline silica into a lymphatic of the legs of rabbits to produce changes which closely resembled those seen in podoconiosis, but Harvey et al. (1996) note that most silica in podoconiosis tissue is amorphous and it cannot be assumed that this has the same effect as crystalline quartz. Frommel et al. (1993) implicate beryllium and zirconium in the genesis of the disease, though Harvey et al. (1996) note that these are unlikely aetiological factors. In Equatorial Guinea the disease is associated with both red clay and black lava soils (Corachan et al., 1988). In the latter areas, the amphibole mineral eckermanite has been implicated in the causation of podoconiosis.

Endemic Kaposi's sarcoma (KS) is a chronic nodular condition that bears a resemblance to podoconiosis in a variety of ways (Ziegler, 1993). The geographic areas of endemic KS conform to those where podoconiosis can be found (i.e. highland, volcanic areas). Furthermore, both are diseases of the lymphatic system that occur in the feet and legs of barefoot peasants, and endemic KS is occasionally preceded by chronic oedema, itching and burning, which are also early symptoms of podoconiosis. Both conditions take years to develop. However, despite such similarities, the diseases do not seem to coexist. In certain regions of sub-Saharan Africa such as the eastern Rift watershed, endemic KS accounts for greater than 10% of adult malignancies. The tumour is associated with immune deficiency, and Ziegler et al. (2001) speculate that Fe-rich soil particles are likely to act by inducing localised immune suppression of the extremities (feet, and less commonly, hands) following penetration of the skin.

The contamination of soils with potentially toxic materials such as dioxins, pesticides, PHEs, polynuclear aromatic hydrocarbons (PAHs) and petroleum products containing PAHs, has prompted the examination and formulation of dermal risk assessment methodologies. Yang et al. (1989) evaluated the percutaneous absorption of the PAH benzo[*a*]pyrene (BaP) in petroleum crude oil sorbed on soil, finding that the absorption of BaP from petroleum crude-contaminated soil was significantly less than the absorption from crude alone. The degree of soil binding of BaP impeded movement into skin to the extent that dermal absorption occurred only from the monolayer of soil in intimate contact with the skin surface. At sub-monolayer soil coverage, the total mass of BaP absorbed decreases proportionately with decreasing soil loading (Roy and Singh, 2001). The sorption of PAHs on soil is generally attributed to the presence of soil organic matter, though 'weathering' or 'ageing' phenomena may result in soil-bound chemicals becoming increasingly desorption resistant over time, so significantly impeding their penetration through the skin (Roy and Singh, 2001). For volatile organic chemicals (VOCs), volatilisation and percutaneous absorption are competing processes. Near-skin VOCs will be partially occluded by outer layers of soil particles, inhibiting evaporation and increasing the fraction available for dermal absorption. Qiao et al. (1997) reports how this contributes to an enhanced dermal absorption of the pesticide pentachlorophenol.

The dermal pathway can contribute a significant or even predominant portion of the risks attributable to contaminated soils. Screening of over 200 Superfund risk assessments from the period 1989–1992 resulted in 19 sites being identified where the dermal/soil pathway was estimated to contribute the largest carcinogenic risk associated with surface soil contamination (Johnson and Kissel, 1996). Yet despite the undoubted importance of dermal exposure to soil contaminants, only a limited number of direct measurements of chemicals absorbed from soil have been made. This factor, together with the lack of knowledge about key exposure parameters (such as the nature, frequency and duration of contact events as a function of type of activity, the area of skin exposed per contact event and the degree and persistence of soiling) indicates that further quantification of the dermal pathway of contaminants remains an important need (Ferguson, 1996).

3. Soils and human health: indirect links

3.1. Soils and the atmosphere

Global warming, caused by an enhanced greenhouse effect, is a major contemporary environmental issue. Although fossil fuel combustion is the main cause of the problem, the importance of soil to the greenhouse effect was brought to the attention of the scientific community at a conference in 1989 and a considerable amount of research has since been centred upon quantifying this relationship. There is an appreciable flux of CO_2 from the oxidation of soil organic matter, whilst soils are also important sources of the greenhouse gases CH_4 and N_2O (Bridges and Batjes, 1996). How people manage the land influences the production and fluxes of these gases (e.g. CH_4 production from paddy soils), and any future climatic warming may increase their emission [e.g. CO_2 from organic soils in the Arctic (Oechel, 1993)], although recent observations of soil carbon stocks and turnover times have implied that warming may not deplete soil carbon as much as predicted by ecosystem models (Thornley and Cannell, 2001). Global warming will cause shifts in the geography of vector-borne infectious diseases (malaria, dengue and schistosomiasis), and alterations in the exposure to thermal stress within populations with consequent thermal-related mortality [e.g. cardiovascular and respiratory mortality (Martens, 1998)]. Rising sea levels might cause serious loss of life, and a change of weather patterns may result in food and water shortages.

A further implication of the greenhouse effect is the acceleration of ozone destroying reactions by cooling the stratosphere. Ozone depletion leads to an increase in UV-B radiation reaching the earth's surface. This has a number of effects on plants and animals, including humans. For the latter there is particular concern about the link between UV-B and the incidence of skin cancer, whilst exposure to enhanced levels of this radiation can also lead to a suppression of the body's immune responses and damage to eyes (especially in the development of cataracts). Loss of ozone is catalysed by a number of reactive atoms or molecules, namely NO, H, Cl and Br. Whilst particular concern has been centred on CFCs and other anthropogenic compounds such as halons, soils as a source of N (as N_2O) and H (as CH_4) contribute to the problem. Furthermore, wetlands have recently been discovered to be a potentially significant source of the methyl halides, CH_3Br and CH_3Cl, to the atmosphere (Varner et al., 1999). Additionally, there is a concern regarding manufactured CH_3Br at present because of its widespread use as a soil fumigant gas. Since this pesticide can be readily released into the atmosphere from the soil, the chemical is threatening to undermine the achievements of the Montreal Protocol (which has reduced emissions of ozone-destroying chemicals by 85% since 1989) with CH_3Br now being the third most important cause of ozone destruction, after CFCs and halons (Pearce, 1999b).

3.2. Soils and the hydrosphere

There is concern about a wide range of potentially toxic compounds that have been detected in both fresh and marine waters located in the remote, and seemingly pristine, Arctic environment. Their occurrence is attributable to a global distillation process in which synthetic chemicals residing in soils as far away as the tropics are vaporised, following which there is long-range atmospheric transport, condensation and precipitation in the cold Arctic latitudes. Research in Canada has shown that this results in a relatively low input of contaminants such as toxaphene (an organochlorine pesticide and a possible human carcinogen) to lakes. Subsequent transfer and biomagnification through exceptionally long food chains can then result in concentrations in fish that are considered hazardous to human health (Kidd et al., 1995). The Arctic marine environment is similarly affected by the global distillation process, resulting in traditional Inuit foods such as muktuk (the skin and surface fat of beluga and narwhal whales) being contaminated with persistent organic pollutants (POPs). For the Inuit, the POPs of primary concern at this time from the point of view of exposure are chlordane, toxaphene and PCBs (Van Oostdam et al., 1999). The developing foetus and breast-fed infant are likely to be more sensitive to the effects of POPs than individual adults, and are the age groups at greatest risk in the Arctic. Recent research undertaken by Dewailly et al. (2000) has shown that prenatal organochlorine exposure could be a risk factor for acute otitis media (inflammation of the middle ear). A reduction of organochlorine body burden in Inuit women of reproductive age is therefore desirable, and can be encouraged by promoting the consumption of traditional food items such as red char that are high in nutrients and low in contaminants. However there is sensitivity in suggesting that traditional foods such as beluga and ringed seal are unsafe, since the harvesting, sharing and consumption of such foods are an integral component of good health among Aboriginal people influencing both physical and social well-being. Consequently, this contamination of traditional food raises problems that go beyond the usual confines of public health. A further problem for the Inuit is that although there are ever increasing restrictions on the use of POPs, the global distillation process may continue to redistribute them from low latitude soils to the Arctic environment for several decades to come (Pearce, 1997).

The discussion above shows how soils can adversely affect the quality of the hydrosphere, in this case by the loss of POPs from soils through volatilisation. In addition to this process, those of erosion, surface runoff, interflow (i.e. water moving sideways through the soil into a watercourse) and leaching can also affect surface and/or groundwater quality. For example, the taste and odour of drinking water is influenced in part by the passage of moisture through soil, dissolving inorganic and organic substances. Thus, under reducing conditions in the soil, excessive amounts of both Fe and Mn can be leached into groundwaters, affecting its taste though it is unlikely in this case to cause a threat to human health (Gray, 1994). Soil acidification causes the increased solubility and leaching of certain elements, including PHEs such as Be, Cd and Al. Particular concern has focused on the latter, with mobilisation from soils attributable to acidification by acid deposition (or other causes such as change of land use) being an example of a so-called Chemical Time Bomb (Konsten et al., 1993). The occurrence of high Al in drinking water has been linked to the development of Alzheimer's disease and other neurodegenerative disorders (Gjessing et al., 1989; Houeland, 1990; Martyn et al., 1989). However, whilst locally increased concentrations of Al occur in the brain of patients with Alzheimer's disease, whether the metal has a causative role in its pathogenesis has still to be definitely established (World Health Organisation, 1996). In Sweden, no correlation was found between the acidification of soils and Hg runoff (Johansson et al., 1991), but in a large part of Scandinavia (and North America) concern has been expressed about this element. This is attributable to air pollution from diffuse sources that, following deposition, has raised concentrations of Hg in the mor humus of forest soils. The Hg is then transported from these soils to surface waters in close association with humic matter to lead to significant increases of the element in fish. In Sweden, Hg contents in pike exceed the blacklisting limit in approximately 10 000 lakes. Consequently, these fish may not be sold or given away, and it is recommended that humans should not consume them. Johansson et al. (op. cit.) concluded that this transport of Hg from the soils will remain high for a very long time, perhaps centuries, even if the atmospheric deposition of this metal is drastically reduced.

Occurrences of high As in drinking water are relatively rare, but in Bangladesh and West Bengal as many as a million water wells may be contaminated with concentrations up to 1000 μg As l^{-1} [far in excess of the limit set for drinking water in Bangladesh (50 μg l^{-1}), or the provisional guideline recommended by the WHO (10 μg l^{-1}) (Nickson et al., 1998)]. The scale of the problem is illustrated by Dhar et al. (1997) who found an area of 51 000 km^2 in Bangladesh, populated by 36 million people, where a significant number of water samples contained in excess of 50 μg As l^{-1}. Consumption of this contaminated water has led to widespread death and disease, and arsenical skin lesions are common. There has been considerable debate concerning the sources of As, and the mechanisms of groundwater pollution in this region. Nickson et al. (2000) and McArthur et al. (2001) propose that the As pollution occurs because Fe oxyhydroxide in the aquifer sediments is microbially reduced, releasing its sorbed load of As to groundwater. The reduction is driven by microbial metabolism of buried peat deposits. Whilst deltaic sediments are mainly associated with this problem, Aswathanarayana (1999) notes the presence of relatively mobile and potentially toxic arsenites (containing trivalent arsenic) in the flooded soils of the province. The reducing conditions of the soil environment facilitate mobilisation and entry of As(III) into the groundwater.

The soil can also supply essential nutrients to drinking waters. Usually such a source accounts for between 2 and 20% of the intake of elements into humans, although F in the form of fluoride is one example where the intake is typically and significantly greater from this source (Fig. 1). There is a recognised link between F and dental health, with water containing more than 0.8 mg l^{-1} conferring protection against tooth decay (World Health Organisation, 1996). This element provides a good example of one that has a relatively narrow concentration range between deficiency and excess (toxic) concentrations. The two primary health effects of high intake of F over long periods are dental (in the form of mottled enamel) and skeletal fluorosis (Fuge, 1988). The WHO recommended limit for F in drinking water is 1.5 mg l^{-1}, but in hot dry regions of developing countries (where factors such as a low protein diet and the high consumption of water makes humans more prone to fluorosis) this threshold should be lower (Dissanayake, 1996). Accordingly, Warnakulasuriya et al. (1992) recommend a level of 0.8 mg l^{-1} for those living in such areas. Drinking water F problems are most commonly associated with groundwaters since these have longer contact times with F-bearing minerals (principally fluorite and apatite) than surface waters. This indicates the importance of rock aquifers in contributing F to water, though the irrigation of F-rich soils can increase the intake of this element through drinking water (or food crops) sufficiently to induce health problems within communities (Mills, 1996).

As a source of Ca^{2+} and Mg^{2+} soils can contribute to water hardness. A considerable number of studies, mainly in the USA, have indicated a negative correlation between water hardness and mortality, especially cardiovascular diseases (e.g. Powell et al., 1982). Such diseases have a complex multifactoral pathogenesis in which clinical (e.g. hypertension) and behavioural (e.g. overnutrition, smoking) factors play predominant roles. The correlation between drinking water hardness and mortality from cardiovascular diseases suggests another causal association, although if so this is likely to be less important than those factors previously mentioned (Masironi, 1979). The explanation for the association between water hardness and heart disease remains unknown, but Edmunds and Smedley (1996) suggest that it is probable that hardness may only be a general pointer towards other agents connected with these diseases. Thus, several hypotheses linking water quality with heart disease have been proposed including: (1) the potential for Ca and/or Mg to protect against some forms of cardiovascular disease; (2) that some trace elements such as Cr, I, F, Li and Mg may be beneficial and more prevalent in hard water; (3) many metals such as Cd are more soluble in soft water and may promote cardiovascular disease. Overall, the general consensus is that moderately hard water is beneficial to human health. This argument is made stronger by the fact that generally the toxicity of pollutants is significantly less in hard water than soft water. For example, organic pollutants tend to be more toxic in soft waters.

Pollution of groundwater by industrial organic solvents is a widespread problem, but any illegal or accidental spillage onto the soil is less likely to contaminate water resources compared to those discharged below the soil layer (Gray, 1994). This is because the soil can be effective in retaining solvents by sorption processes, allowing longer periods for the soil bacteria to break down the organic molecules. Soils are also very important in determining the fate of pesticides. These may reach the soil in a variety of ways: the disposal of livestock dip on farmland; in drip from plants; as seed treatments; root dips; spray that does not contact the target organism; and by the decay of plant and animal tissues that have been exposed to pesticide applications. Some pesticides are directly applied to the soil, as in the case of the soil fumigant CH_3Br previously mentioned. The pre-emergence herbicides atrazine and simazine, and aldicarb (trade name Temik, an insecticide) are further examples of soil applied pesticides. From the soil, transport of pesticides can pollute both surface and groundwaters (Ritter, 1990; Wauchope, 1978) with some concentrations exceeding permissible values. Williams et al. (1991) recorded the concentrations of simazine found in a stream draining a small catchment subjected to normal agricultural practice in the UK. Peaks in the concentration of the herbicide occurred very soon after precipitation. Although only less than 1% of the total volume of simazine reached the stream following each rainfall event, concentrations reached a maximum that was approximately 700 times higher than the EU maximum admissible value (0.1 $\mu g\ l^{-1}$). Atrazine and simazine are two of the most common pesticides found in UK drinking waters, and consequently they have been placed on the countries 'red list' of priority pollutants (Alloway and Ayres, 1993). Groundwater contamination following leaching is a possible hazard associated with the use of aldicarb (Baron, 1994), and in the US this concern is currently being addressed in the Special Review process (EPA, 2000).

At present it is difficult to quantify the risk of any raised concentrations of pesticides in waters since most studies have concentrated on the major organochlorine compounds (many of which are now banned) and little has been undertaken on the newer varieties. Laboratory studies show that pesticides can cause health problems, such as birth defects, nerve damage and cancer, and children may be especially sensitive to pesticide exposure. In recent years a growing body of evidence has indicated that some synthetic chemicals, including pesticides, may be interfering with normal human endocrine system functioning (Colborn et al., 1996). In the U.S., the Environmental Protection Agency regulates certain chemicals that are suspected of being endocrine disruptors by establishing maximum contaminant levels under the Safe Drinking Water Act (EPA, 2001). But even if permissible values for individual pesticides are not exceeded, the cocktail of these chemicals commonly found in drinking water may have health implications that at the moment are unknown (Gray, 1994). A further complicating factor is that there are other sources of exposure of pesticides to humans. It is commonly assumed that the intake of pesticides is much higher from food than from water. However for some people drinking water may be the major source of exposure (Fielding and Packham, 1990), and clearly soils have an important role in determining the fate of pesticides in the environment and the concentrations found in surface and groundwaters.

The NO_3^- anion is very soluble in water and being negatively charged is not adsorbed to any marked extent by most soils. Consequently, the anion is highly mobile and subject to major leaching (and surface runoff in some situations) losses when both soil NO_3^- concentration and water movement are high. In rural catchments agricultural sources are the most significant contributors to the nitrogen load of receiving waters. For example, mineralisation of soil organic matter and crop/animal residues provides much of the NO_3^- leached during winter under the climatic conditions of north-west Europe, because the mineralisation is poorly synchronised with crop N uptake (Powlson, 1993). Fertilisers are another source, although their contribution to raised NO_3^- concentrations in waters has often been over emphasised (Addiscott, 1996). The links between land use practices and the NO_3^- content of surface and groundwaters are difficult to clearly isolate, but the economic and environmental implications are of such importance so as to make the 'nitrate issue' a major focus of study. This is especially since the problem has shifted in scale from local to regional dimensions, attributable mainly to the intensification of agriculture (Heathwaite et al., 1993). For human health there are two key areas of concern. Infantile methaemoglobinaemia ('blue-baby' syndrome) arises where ingested NO_3^- impairs the oxygen-carrying capacity of the blood. Initial concern about this problem arose over 50 years ago (Comly, 1945), although the incidence is low with the WHO reporting just 2000 cases world-wide between 1945 and 1986. Certainly the condition is very rare in most developed countries with an extensive piped mains supply, although elsewhere in rural societies that are more dependant upon well water there remains a hazard to the unprotected child (Hill, 1999).

A potentially more serious threat from high nitrates in drinking water is the proposed link with stomach cancer. O'Riordan and Bentham (1993) reviewed the mixed results concerning this issue within the UK, concluding that the epidemiological evidence does not provide any strong support for such an association. More recently, McKnight et al. (1999) came to a similar conclusion. Indeed, these authors express doubts about whether the substantial costs of reducing nitrate pollution can be justified on the grounds of avoiding these health risks. The more recent realisation that dietary NO_3^- may have beneficial effects on the physiology of the intestinal tract and that it may protect humans against food and water-borne pathogens strengthens this argument. This issue remains hotly debated however, with Hill (1999) stating that the current EU and WHO legislation remains reasonable. Furthermore, controlling NO_3^- runoff and leaching may be justifiable in terms of preventing eutrophication episodes. In waters where nutrient enrichment has led to eutrophication, toxic cyanobacteria (blue-green algae) species may dominate phytoplankton blooms. Cyanobacterial toxins can cause a variety of human illnesses including gastroenteritis disorders, atypical pneumonia, allergic and irritation reactions and liver diseases including cancer (Bell and Todd, 1996).

The deposition of faeces from human and other animal sources onto soils can potentially infect water supplies with bacteria, protozoa (*Cryptosporidium, Giardia*) and viruses (Rose, 1990). For example, *Escherichia coli* 0157 is a virulent human pathogen that can result in a wide spectrum of clinical symptoms including most commonly haemorrhagic colitis (bloody diarrhoea) (Jones, 1999). Cattle are the primary reservoir of this bacterium, and consequently there are serious implications for the land-based disposal of cattle manure and slurry and abattoir waste. Once in the soil, *E. coli* can remain viable for several months, although there is a paucity of data on the behaviour of the pathogen in different soil types. Whilst most common causes of *E. coli* 0157-related poisoning have been associated with the consumption of contaminated meat and dairy products, there is also evidence that human infection has occurred through the ingestion of, amongst other things, contaminated soil and drinking water.

In the US, the occurrence of antibiotic resistance genes in groundwater provides a possible way for humans to acquire antibiotic-resistant infections. Antibiotics such as tetracycline are routinely added to livestock feed to promote animal growth. The analysis of samples from farm waste lagoons and nearby groundwater reservoirs has revealed that bacteria in the soil and groundwater carried tetracycline resistance genes that were almost identical to those in bacteria living in the animals' guts (Chee-Sanford et al., 2001). This research strongly suggests that the animal bacteria are transferring their genes into other ecosystems. With approximately 40% of the water used for public supply in the US coming from groundwater (and this value will increase throughout the century) (USGS, 2001), this recently identified problem may be widespread. In the European Union, animals con-

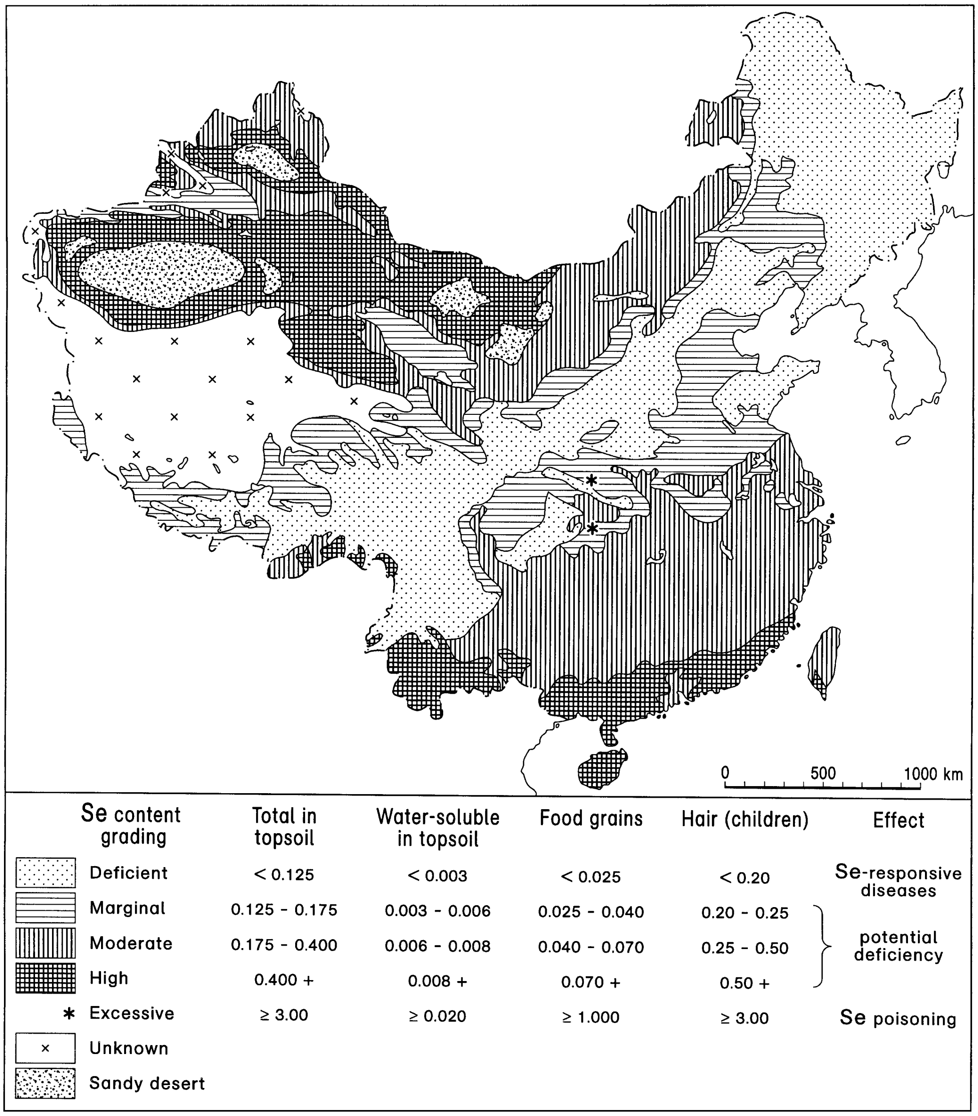

Fig. 3. The selenium ecological landscape of China (adapted from Tan, 1989). Keshan disease and Kaschin–Beck disease are mainly associated with the Se-deficient landscape that is found from the north-east to the south-west of the country. Selenium toxicity (selenosis) resulting in hair and nail loss and nervous system disorders has also been recorded in areas of elevated soil Se content. Concentrations are in mg kg^{-1}.

sume some 5000 tonnes of antibiotics every year. No ceiling on the amount of farm drugs allowed into soils exists, but veterinary authorities across the EU had stated that any compound likely to accumulate at above 7.5g per hectare on a farm must undergo an environmental impact study. Alarm from environmental regulators was expressed in early 2000 by the news that the threshold was to be raised to 75 g per hectare (Pearce, 2000).

Aside from water used for drinking, recreational waters can also be contaminated with faecal bacteria from ‘catchment’ sources. Working in a number of areas within the UK, Kay et al. (1999) have quantified the contribution of faecal indicators delivered to nearshore coastal waters from the sewerage system and riverine inputs. The sewerage system dominates during low flow conditions, but is often overtaken by riverine inputs during high flow conditions after rainfall that flushes faecal bacteria from the soil. The scale of the problem can be made with reference to Wales, a predominantly rural principality. Here, the human population equals 2.2 million whilst the sheep population exceeds 11 million. Since the faecal coliform production by a single sheep is approximately five times the human output, the sheep population within Wales is equivalent to a human population without sewerage of some 55 million. It is for such reasons that many UK bathing beach locations exhibit non-compliance after rainfall when stream inputs, rather than sewerage inputs, commonly dominate. This problem has recently been recognised by the European Commission and the World Health Organisation who have separately suggested that bathing beach management should accommodate prediction of the natural background variations in indicator bacterial concentrations from diffuse sources. This real time prediction offers a new paradigm in compliance assessment and public health protection through real time beach management rather than the traditional 'end of season' calculation which offers little scope for appropriately timed public information (European Union, 2000; World Health Organisation, 2001).

3.3. Soils and the biosphere

There is no doubt that the geochemical environment has a profound influence on the level of health in human societies. Some elements are essential mineral nutrients, with a requirement throughout life and whose absence produces specific deficiency symptoms. In this respect Ca, Cl, K, Mg, Na, P and S are regarded as essential macronutrients since a daily requirement of 100 mg or more is needed by individuals (Crounse et al., 1983a). In comparison Co, Cr, Cu, F, Fe, I, Mn, Mo, Se and Zn are essential micronutrients with a human requirement of no more than a few mg d^{-1}. Furthermore, some elements (Ni, Si, Sn and V) are likely to be essential micronutrients, although their positive role in human nutrition remains to be confirmed. In contrast all trace elements are toxic if their intake through ingestion or inhalation is excessive. In particular Ag, As, Be, Cd, Ce (?), Ge (?), Hg, Pb and some of the daughter products of U are good examples of PHEs that have no proven essential functions in humans, and are known to have adverse physiological effects at relatively low concentrations (Plant et al., 2000). Some routes of mineral nutrients and PHEs to humans have already been explained in this review. For example, accidental or deliberate soil ingestion results in a direct geochemical pathway of elements to humans. However, the transfer from soil to human (plant and animal) foods is for many elements an important and more indirect exposure route to people (Fig. 1). Consequently, deficiencies, excesses, or imbalances in the supply of inorganic elements from such dietary sources can have an important deleterious influence on human health (Mills, 1996). Despite this, known causal relationships between health problems and the elements in human foods derived from the immediate soil environment are limited. Crounse et al. (1983a) consider this to be due to the numerous variables involved, the difficulties of arranging and undertaking experiments on human subjects, and the fact that epidemiologic evidence seldom proves causality. Because of these factors the majority of the links between human health and soil geochemistry/diet remain 'suggestion, hypothesis, speculation and conjecture' (Crounse et al., op. cit., 270). The essential micronutrient Mo provides a good example where a dietary excess or deficiency linked to soil concentrations may cause health problems, but the associations require closer examination before a definite causal relationship can be established. The intake of this element by humans is increased both when soil Mo concentrations are high and when its uptake into foods is promoted by neutral/alkaline conditions, particularly where soils are poorly drained. Kovalsky et al. (cited by World Health Organisation, 1996) claims that this gives rise to the abnormally high incidence of gout in Mo-enriched regions within Armenia. Elevated environmental Mo concentrations have also been associated with a reduced caries prevalence

(Davies and Anderson, 1987), whilst in Transkei (South Africa) a deficiency of this element in locally produced foods such as maize, beans and pumpkins has been linked to a high incidence of oesophageal cancer (Burrell et al., 1966).

Mineral nutrient deficiencies in humans may arise for a variety of reasons and are not solely attributable to low soil/dietary concentrations. The World Health Organisation (1996) notes that there is particular concern about F, Fe, I and Se deficiency problems. Furthermore, the same report concludes that Zn should be added to this list especially since population groups in developing countries can consume diets from which Zn is of low bioavailability. For Fe, poor diet, blood loss and periods of higher requirements (growth, child-bearing) are the most common causes of deficiency (Crounse et al., 1983a). The soil composition affects the amount of Fe in food, although Fe absorption by humans depends not only on the food content, but also on the form of iron, other plant substances such as phytate, and the presence of antagonistic elements such as Co, Cu, Zn and Mn. Zinc availability is similarly reduced by antagonism with Ca, Cu, Fe, Ni and P, whilst a phytate/Zn ratio that exceeds 15 will lower absorption [the World Health Organisation (1996) notes that phytate is one of the principal dietary factors inhibiting Zn absorption]. Deficiency symptoms of Zn in humans include a failure to eat, severe growth depression, skin lesions, sexual immaturity, depression of immunocompetence and decreased acuity of taste (hypogeusia) (Kiekens, 1995). According to Crounse et al. (1983a) there is much evidence of widespread marginal Zn deficiency problems, although soil/diet geochemical influences on Zn in humans are not nearly as evident as for the elements F, I and Se. Zinc deficiency can occur through a variety of causes that will have the effect of masking soil/diet geochemical influences. For example, hypozincaemia was commonly found by Cheek et al. (1981) amongst the Aboriginal people of north-west Australia. Whilst the soils of the study area are low in Zn, other factors (decreased absorption attributable to geophagy and phytate and an excessive loss of Zn due to intestinal parasites and perspiration) are also important in this region. Although soil/diet geochemical influences are not as evident for Zn as for some other elements, Crounse et al. (1983a) conclude that such influences could be quite important bearing in mind the occurrence of widespread marginal deficiencies. According to the World Health Organisation (1996), deficiencies of Zn associated with anomalies in human food chains may be expected in areas of calcareous soils from which Zn uptake is limited, and leached arenaceous soils of low Zn content.

Iodine is an essential constituent of the thyroid hormones, thyroxine [3,5,3′5′-tetraiodothyronine (T_4)] and 3,5,3′-triiodothyronine (T_3), that play an important part in the growth and development of humans. Goitre, the enlargement of the thyroid gland causing a swelling in the front part of the neck, is the visually obvious feature of a deficiency in this element, though this rarely poses a major health problem. Other iodine-deficiency disorders (IDD) include stillbirths, abortions, congenital abnormalities, endemic cretinism (characterised by mental deficiency, deaf-mutism, spastic diplegia and lesser degrees of neurological defect) and impaired mental function (Stewart and Pharoah, 1996). An estimated 29% of the world's population are at risk because they live in an I-deficient environment. Six hundred and fifty-six million people have goitre, and 43 million some degree of mental defect, including 11.2 million overt cretins (World Health Organisation, 1996).

The two most important criteria that control the I content of soils are the availability of a supply of the element, and the ability of soils to retain it [i.e. the iodine fixation potential (IFP); Fuge and Johnson, 1986]. With seawater being the most important reservoir for terrestrial I, coastal soils are enriched in the element relative to those in rain shadow and central continental areas. As a result, IDD are commonly, although not exclusively, found in areas remote from the coast. Fuge (1996) suggests that the element can migrate in a series of steps across landmasses by deposition followed by revolatilisation, although soils of high pH and organic matter content (i.e. soils of high IFP) would act as a migration barrier, retaining the element in a non-bioavailable form. This could explain the historically recorded occurrence of IDD in areas of the UK that have soils enriched in this element, such as the limestone regions of Derbyshire, north Oxfordshire and south Wales, and the peat moorlands of south-west England. Dissanayake and Chandrajith (1996) also highlight the importance of soil organic matter, pH and clay mineralogy on the bioavailability of I in Sri Lanka, a country where the prevalence of endemic goitre is extremely high (up to 44%) in certain regions. The association between the endemic goitre belt of this country with the wet climatic zone suggests that leaching of the element is also important in the causation of IDD, although according to Stewart and Pharoah (1996) such a hypothesis is frequently overstated. A further complicating factor in the causation of IDD is the presence of goitrogens that affect the utilisation of the element by the thyroid gland. Many goitrogens have been implicated such as thiocyanate released from inadequately prepared cassava, and as a source of elements such as As, Ca, Co, F, Mg, Mn, Se and Zn, soils may contribute so-called geological goitrogens to the diet (Fuge, 1996). There may be a link between such geological goitrogens with plate subduction zones. In northern Pakistan, several suspected goitrogens are concentrated in minerals within rocks of the Asian non-subducting plate. Goitre is particularly prevalent here, and a hypothesis has been put forward that weathering releases the geological goitrogens to the soil and food chain (Stewart, 1990). Goitre is also more prevalent in other non-subducting plate regions, such as the Andes, the Himalaya–Indonesia–New-Guinea belt, the Philippines and Turkey, suggesting that mineral assemblages in the rocks of these areas are a source of goitrogens following weathering.

Keshan disease (KD), an endemic degenerative heart condition (cardiomyopathy) usually characterised by moderate to severe heart enlargement with varying degrees of malfunction that can lead to death, is associated with a deficiency of soil Se. The disease prevails in a north-east to south-west belt of China (Fig. 3), although ‘safety islands’ are found within this area (Chen et al., 1980). Tan (1989) also notes the presence of KD in Korea. This disease mainly affects children aged under 15 years, and women of childbearing age. Keshan disease was a major health problem several decades ago, but economic development and a greater diversity of dietary sources have made new cases rare. Supplementation has also proved effective. Chen et al. (1980) reported that incidence rates of 9.5–13.5/1000 in 1974–75 were reduced to 1–2/1000 in children treated with a weekly tablet of 0.5–1 mg sodium selenite. These authors noted the low concentrations of Se in the local cereals and vegetables of the affected areas, resulting in the intake of this element from such staple crops being less than the minimum dietary requirement of Se needed for the maintenance of normal human health (20–30 $\mu g\ d^{-1}$). Keshan disease can also be found in areas of high soil Se. For example, Johnson et al. (2000) investigated 15 villages within the Zhangjiakou district (north-east China), and found that the soils from the high-incidence KD villages had the greatest total Se concentrations. The bioavailability of the element in such soils, however, was reduced because of the organic matter content and pH (<7.6). This led the authors to conclude that soil colour could be effectively used as a low-tech visual indicator for assessing the KD risk in a village (organic enriched, dark soils being more likely to be associated with a high KD incidence relative to lighter, yellow sandy alluvial soils), since small changes in organic content (and pH) can have a critical effect on the disease status of a village.

There are certain epidemiological aspects of KD (e.g. its seasonal variation) that are difficult to explain solely on the basis of Se deficiency (World Health Organisation, 1996). This suggests that additional factors such as a virus, a low intake of vitamin E, or a low intake of elements such as Mo, may be possibly relevant to the aetiology of the disease. Selenium deficiency in China has also been linked to an endemic osteoarthropathy known as Kaschin-Beck disease that causes a deformity of affected joints. This disease in China is found within the same geographical areas as KD (Fig. 3), and has also been reported from Siberia (where it has been referred to as Urov disease) and the northern mountainous area of Korea. As with KD, other variables such as *Fusarium* contamination of grain, and humic acids in drinking water, may be additional important factors in the pathogenesis of this disease.

Selenium toxicity (selenosis) has also been reported from China (Fig. 3). Yang et al. (1983) note the discovery of selenosis in 1961 within Hubei Province. The most common sign of poisoning was a loss of hair and nails, but in the areas of highest incidence, lesions of the skin, abnormalities of the nervous system and mottled teeth were also noted. Here, weathering of a stony coal of very high Se concentration (average 300 mg kg^{-1}) results in soils of elevated Se content. Liming increases the uptake of the element into crops, but the authors note that this particular outbreak of selenosis was due to a drought that caused failure of the rice crop, forcing villagers to eat vegetables and grain of higher Se content and fewer protein foods. Working in the same area of China, Fordyce et al. (2000) noted that areas of Se deficiency (and KD) and selenosis occur within 20 km of each other, attributable to underlying geologic variations. Not all the ‘high’-Se villages had toxicity associated with them, and within individual villages Se concentrations can vary from deficient to toxic making risk assessment difficult.

High concentrations of F in drinking water are mainly considered to be the chief cause of endemic fluorosis. Despite this, foods containing high amounts of F should not be disregarded, and Huo (1981) notes the link between F-containing foods and fluorosis in Vietnam, Thailand and China. This author recorded 34 cases of foodborne endemic skeletal fluorosis among the residents of the county of Guizhou (China). Here the F content of drinking water is very low, but the acidic soils favour uptake of the element into food crops. The average F content of seven staple foods ranged from 8.3 to 11.7 mg kg^{-1}, but tea showed the highest concentration (range 35.1–59.2 mg kg^{-1}). Tea is well known to concentrate F in its leaves, and substantial amounts are released during tea infusion (Fung et al., 1998). A new type of local F disease, tea-induced fluorosis, was discovered in Urumqi county in 1988 (Kang et al., 2000). Here, the high intake of F (10.1 mg d^{-1}) through a large consumption of so-called brick tea affects mainly the Karak inhabitants, though other ethnic groups are likely to suffer as well. This study revealed that some 33% of children had a detectable rate of dental fluorosis, and 16% of adults a detectable rate of skeletal fluorosis. Brick tea is produced mainly from old leaves that are known to concentrate F. Accordingly, Ruan and Wong (2001) suggest that in order to eliminate the hazard of over-exposure to F derived from tea, younger shoots should be used, and mature leaves avoided.

In China, high-F containing soils can also contribute to poisoning in another way: Finkelman et al. (2001) noted the tradition in Guizhou Province of eating corn dried over burning briquettes made from high-F coals and high-F clay binders. Such practices contribute to more than 10 million people suffering from dental and skeletal fluorosis, but Finkelman et al. (op. cit.) note that not all the local clays are enriched in F, and the problem could be reduced by using low-F clays identified following geochemical mapping procedures.

Raised concentrations of elements in soils result not only from the weathering of geochemically anomalous parent materials (such as ultrabasic rocks) and mineral ore bodies, but also from human activities such as industrialisation, mining/smelting, agriculture and urbanisation. These activities can have implications to human health, with excessive concentrations of elements entering the food chain. Edwards et al. (1995) report that some food crops can accumulate significant quantities of thallium (symbol Tl) even from soils containing relatively low amounts of this metal. The most notable cause of Tl poisoning occurred adjacent to a cement works at Lengerich (population approx. 20 000), Germany. Here, large numbers of people were diagnosed as suffering from Tl-related health problems including depression, insomnia and various nervous disorders. The majority of the population (>95%) consumed more or less frequently vegetables and fruit grown in private gardens, the consumption of which constituted the major route of the population’s increased intake of Tl (Dolgner et al., 1983). Concentrations of the metal were also found to be high in the livers and kidneys of domestic animals. A significant decrease of Tl in urine samples from the affected population followed substantial changes of diet attributable to an official recommendation to avoid the consumption of locally grown vegetables and offal from domesticated animals.

The nuclear industry constitutes a potential threat with released radionuclides entering food chains from the soil and causing a radiological hazard. Fuge (1996) notes that ^{131}I, a potentially dangerous radionuclide since it has a particularly high specific activity, can pass rapidly through the food chain to become concentrated in the thyroid gland where it can lead to an increased risk of cancer. The accident at the Chernobyl reactor in the Ukraine on 26 April 1986 has led to the contamination of food chains with radionuclides that still exist today, and will continue to pose a threat to human health for decades to come. Following this accident, in the UK unexpectedly large concentrations of ^{137}Cs and ^{134}Cs were recorded in *Calluna vulgaris* and *Vaccinium myrtillus*, important upland plant species that efficiently exploit the base-poor soils supporting the rough pastures found in north Wales and Cumbria (Bell et al., 1988). Subsequent transfer into grouse, sheep and honey has posed a threat to human health that still continues. Smith et al. (2000) have investigated why such an unexpected long-term hazard has occurred, and conclude that a sorption–desorption process of radiocaesium is tending towards a reversible steady state. Initially following fallout, ^{137}Cs mobility and bioavailability was controlled by a slow diffusion of the radionuclide into clay mineral lattices. Studies indicate that this process is reversible, with a mobility of ^{137}Cs into the environment meaning that foodstuffs are remaining contaminated for much longer than originally expected. The result is that in the UK restrictions on the sale and slaughter of approximately 232 000 sheep remain, and the authors conclude that such measures may need to stay in place for a further 10–15 years — more than 100 times longer than originally estimated. In some areas of the former Soviet Union, consumption of fruit berries, fungi and fish will need to be restricted for at least a further 50 years (Smith et al., 2000b).

Perhaps the best known example of metal contamination of soils that has caused health problems through the contamination of foodstuffs is itai-itai disease recorded from a 67.7 km^2 area in Toyama Prefecture, Japan. Tsuchiya (1978) records that the patients of this disease were mainly women, complaining of severe pain in the joints and bones, particularly in the breast and pelvic areas and the upper and lower extremities. The severe bone decay (osteomalacia) was accompanied with serious damage to the kidney (renal tubular dysfunction), and following death autopsies revealed high tissue Cd concentrations. The existence of itai-itai (the Japanese word itai means 'ouch' or 'painful' in English) was first made public in 1955, with the Japanese Government officially announcing in 1968 that Cd-contaminated food, especially rice and possibly water, was the main cause. Kamioka mine was identified as the source of the Cd, releasing the metal into river water that was then used to irrigate rice paddy soils. A peak in the prevalence of the disease occurred shortly after the second world war, coincident with the highest levels of environmental pollution. However, the development of itai-itai disease is not fully explained by excess Cd concentrations, and other factors such as malnutrition are thought to have contributed to this health problem.

Epidemiologic estimates from Japan suggest that daily Cd intake by the oral route should be kept below 180–250 μg to prevent damage to the kidney. In general, human diets are estimated to contain between 50 and 150 $\mu g\ d^{-1}$ of Cd, the latter level seeming sufficiently high to cause at least subtle effects in humans, especially if combined with predisposing factors (e.g. multiple pregnancies, malnutrition), additional Cd sources (e.g. smoking) or a diet containing unusually rich sources of the metal (e.g. beef liver, oysters) (Crounse et al., 1983b). Sewage sludge-amended soils can contain sufficiently high concentrations of Cd to cause elevated amounts of the metal in food crops, and there is a European Directive limiting the maximum Cd content of sludged soils to 3 $mg\ kg^{-1}$ (Alloway and Ayres, 1993). Although sewage sludge applications are considered a major source of Cd in soils receiving sludges, the most important anthropogenic sources overall are phosphatic fertilisers and industrial emissions. Thus in Sweden, concern has been expressed about the effects of atmospheric and fertiliser inputs in raising soil Cd concentrations, and of acidification in enhancing the uptake of the metal from soils into vegetables with a high metal uptake potential such as lettuce and cabbage (Environmental Resources Ltd., 1983).

In the UK, the discovery of large amounts of Cd in agricultural and garden soils at Shipham (population 1000) that exceeded by an order of magnitude the concentrations associated with the occurrence of itai-itai disease, resulted in one of the most ambitious environmental health investigations ever mounted. Much of the parish of Shipham is built upon the site of Zn mineralisation and historical mining/processing activity (Morgan, 1988). As a result of the geology and mineral working, high but variable total concentrations of Cd, Hg, Pb and Zn are found in soils of the area. Thornton (1988) records Cd concentrations in agricultural soils in excess of 1000 mg kg^{-1}, whilst surface garden soils within Shipham ranged up to 360 mg kg^{-1}, with a median content of 91 mg kg^{-1}. From 235 samples of surface garden soils sampled at the control area, a median value of 0.6 mg kg^{-1} was determined. However, the very small proportion of soluble Cd (approx. 0.04%) in the soils sampled at Shipham indicates that most of the metal is strongly sorbed by soil constituents. Alloway et al. (1988) attribute this to the high pH (7.5–7.8), high $CaCO_3$ and high hydrous oxide content of the soils found at Shipham. Although the proportion of Cd in the soil solution is low, because of the uniquely high total soil Cd concentrations, the amount available for plant uptake is still higher than in normal soils. Consequently, garden crops grown at Shipham contain higher than normal amounts of Cd. The average concentration of just over 0.25 mg Cd kg^{-1} (fresh weight) compares to the UK average of 0.015 mg kg^{-1}; leafy vegetables such as cabbage, spinach and lettuce, and root crops including leeks, contained the highest amounts. Surveys carried out at Shipham showed that Cd dietary intakes were higher than average for the UK (Morgan, et al., 1988). However, intakes at Shipham usually fell well within the Provisional Tolerable Weekly Intake (PTWI), and only four participants (6% of the sample population) had values that exceeded the PTWI of 0.4 mg per week (these were mainly people who consumed large amounts of locally grown produce). Health studies showed that statistically significant differences between the populations studied at Shipham and the control area was found for many of the biochemical parameters measured (Strehlow and Barltrop, 1988). While the differences were in the direction expected if Cd were to have an effect on the human population, there was no evidence of adverse health effects.

A comparison between Shipham and the itai-itai disease area of Japan is worthy since important conclusions about contaminated soils with PHEs and their impact on human health can be drawn. The paddy soils in Japan contain lower total concentrations of Cd (by an order of magnitude or more), but the acidic (pH 5.1), low carbonate and low hydrous oxide content of the gleyed soils result in a significantly higher percentage of soluble Cd (approx. 4%), relative to the Shipham area (approx. 0.04%) where the free draining soils have a greater sorption capacity. The greater bioavailability of Cd leads to an elevated intake of the metal, and such intakes are further increased by the fact that the affected Japanese had a restricted diet consisting of crops (principally rice) grown on the contaminated soils. This leads to the conclusion that people with a greater diversity of diet (e.g. as generally found within prosperous societies) are less vulnerable to the soil geochemical environment than those reliant on a more restricted food intake. Secondly, whilst soils may contain high total concentrations of elements, factors including soil pH and drainage and redox potential, influence the speciation, mobility and bioavailability of elements to plants. Furthermore, the soil–plant relation is affected by factors such as the species of plant, stage of growth and season, whilst the relation between elements in plants and the amounts absorbed by domesticated grazing animals is influenced by factors such as the composition of diet and its digestibility, and the form and availability of the ingested elements (Thornton and Webb, 1979). The implications of these observations are that there are often a number of effective barriers operative in the transfer of PHEs from soils to food produce that restrict uptake into the food chain. The region of south-west England may be taken as an appropriate example to illustrate this. As a result of mineralisation and historical mining/ore processing, over 1000 km^2 of land has been classified as highly or moderately contaminated by one or more of the elements As, Cu, Pb and Zn (Abrahams and Thornton, 1987). Folklore associates a number of localities in south-west England with various forms of illness caused by the adverse effects of the mineralised ground and the mining industry. Studies have indicated a higher than average mortality rate or an elevated prevalence of cancer, multiple sclerosis and tooth decay in these areas (Allen-Price, 1960; Anderson et al., 1976; Hargreaves, 1960; Warren and Delavault, 1967), though such reports lack the sophisticated statistical techniques necessary for thorough epidemiologic investigations (Shaper, 1979). Clough (1980) further suggests that the distribution of As in this environment is an aetiological factor for the high incidence of melanoma of the skin in south-west England. There is also some anecdotal evidence to suggest that local inhabitants may develop a natural tolerance to the high soil concentrations encountered in their environment, since non-local people who have moved into contaminated areas have supposedly suffered from As poisoning caused by the consumption of home produced vegetables grown in gardens reclaimed from former mine dumps (Thomas, 1980). All these observations remain to be confirmed, but research investigating the uptake of elements such as As indicate that the consumption of locally produced food is not hazardous. For example, in the Tamar mining area, on soils ranging from 20 to 300 mg As kg^{-1}, the As content of barley grain increased with soil content, but in no case contained more than 0.4 mg kg^{-1} DM (Thoresby and Thornton, 1979). A study of garden soils in south-west England revealed As concentrations up to 892 mg kg^{-1}, yet the amounts of this element in six salad and vegetable crops were only slightly elevated and below the UK statutory limit of 1 mg kg^{-1} fresh weight (Xu and Thornton, 1985). In this work, Fe was found to be a soil constituent that lowered the bioavailability of As to crops, and the authors further concluded that the plants are acting as ‘geochemical barriers’ in the environment and are only making a small contribution to the exposure of this element to humans. As a result of this limited uptake, Hughes (1979) concluded that an 80-kg person could only achieve the maximum acceptable daily load of As by eating 5.9 kg of the most contaminated broccoli encountered in south-west England. Mitchell and Barr (1995) looked at all possible exposure routes of As to humans in south-west England, and concluded that there is insufficient evidence to positively implicate the intake of this element with cancer and other diseases in the general population. Natural precautions should be undertaken (e.g. washing of food produce), but otherwise it is not thought that exposure through locally grown foods is in any way hazardous. Instead, accidental ingestion of As-contaminated soil and dust is the main exposure to humans especially children, and this warrants further investigation (Farago et al., 1997).

4. Discussion and conclusions

The preceding sections illustrate the diversity of ways in which the health of all humans is influenced by their interactions with the soil, either deliberately or involuntarily, and directly or indirectly. Some people may interact with the soil more than others because of their behaviour (e.g. young children prone to hand-to-mouth activity), profession (e.g. agriculturalists, archaeologists) or socio-economic status (e.g. people of poor rural societies), but even communities remote from certain soils can have their health significantly affected (as demonstrated by the Aboriginal people of northern Canada suffering the consequences of the global distillation process). In some cases the impact of soil on human health has been established for an appreciable time period, and soils have affected certain aspects of human health throughout history. Soil I provides a good example of these observations. It has been known for approximately 70 years that a lack of this element in the diet is responsible for goitre and cretinism, while the Hindu and Chinese literature of 4000 years ago make reference to neck swellings (goitre) (Langer, 1960). Other impacts of soils on human health have only been appreciated relatively recently. This is attributable partly to the emergence of new knowledge and discoveries such as, for example, the recently reported practice of geophagy in certain Asian communities within the UK (Abrahams, 2002). New risks also link soils to human health. As an example, much of the recent interest in the geochemistry of I in the secondary environment is related to concern about the fate of ^{131}I released from nuclear installations.

Invariably, there has been an emphasis in this review on the deleterious impacts that the chemical, physical and biological properties of soils pose to human societies. To balance this it must be remembered that soils significantly influence a variety of functions (e.g. as a plant growth medium; its importance on the cycling of water; as a foundation for buildings) that sustains the human population. Furthermore, soils have been utilised throughout human history as a pharmaceutical (Black, 1956; Root-Bernstein and Root-Bernstein, 2000), and are still used for the effective treatment of gastrointestinal disorders, cases of poisoning and externally as a dusting powder and poultice (Martindale, 1993). Soil micro-organisms are the main producers of natural antibiotics. In this respect, soil fungi have yielded a large number, the most important of which is penicillin, while anaerobic spore-forming bacilli are also active. More than 50% of the antibiotics described are produced by members of only one bacterial order, Actinomycetales, and particularly by one genus of this order, *Streptomyces*. From these organisms the soil microbiologist S.A. Waksman and colleagues discovered a number of antibiotics including (in 1943) streptomycin which is active against a wide number of bacteria including *Mycobacterium tuberculosis*. For such studies, Waksman was awarded the Nobel Prize in Physiology and Medicine in 1952, and since then much research has been devoted to the isolation and investigation of numerous soil actinomycetes, with many antibiotics discovered and applied in human medicine.

While research into antibiotics derived from soil organisms has been ongoing for several decades, another (controversial) aspect of the beneficial role of soil organisms to human health has started to be appreciated only in the last few years. This involves the so-called 'hygiene hypothesis', as described by Folkerts et al. (2000), which attributes the increase in the prevalence of allergic and autoimmune diseases that have been observed in affluent societies over the past 20 years to (in part) a decreasing human exposure to soil mycobacteria (Rook and Stanford, 1998). In a similar manner, a recent decline in intestinal worm infection (e.g. of *Ascaris lumbricoides*) in people of developed societies may be the cause of the increasingly common inflammatory bowel diseases that are now being recorded (Coghlan, 1999). These examples suggest the importance to humans of interacting with soils, and indicate that modern urban societies may experience health problems since their contact with soil, and the potentially beneficial organisms they contain, is reduced.

Some impacts of soil on human health are obvious and dramatic, as demonstrated during 1999 by the catastrophic debris flows which (combined with flash flooding) resulted in the loss of tens of thousands of lives in Venezuela following a high magnitude storm. Arguably, some of the problems concerning humans and soils (e.g. the links between soils and global warming) may trigger the types of controls (famine, pestilence and social unrest) that Malthus suggested would occur if population growth could not be controlled. Other problems that soils pose to the health of humans can be more subtle, to the extent that it is difficult to fully establish the importance of soil to a particular health problem. Subclinical manifestations of a disease can mask the links between soil and health, whilst other factors such as the diversity of a human diet, the mobility of people, the multifactorial causes of disease, and the difficulties of undertaking observations and experiments on humans all contribute further to the problem. Maps showing the incidence or mortality rate for a particular disease are a simple and traditional way of presenting medical data (e.g. Gardner et al., 1983, 1984). Such maps frequently show a spatial variation of diseases that are not a reflection merely of errors and biases in the basic data, suggesting that environmental factors are operating. It is very tempting to correlate medical data with environmental factors such as soil multi-element geochemical information. Frequently this results in producing a large number of significant correlation coefficients that can lead to the development of disease hypotheses. However correlation does not prove causation, and there are a number of problems associated with this type of statistical analysis (Bølviken and Bjørklund, 1990). Such problems are not restricted to studies centred on soil geochemistry: in south-central England an association between soil wetness and infant mortality has been reported (Munro et al., 1997). Overall, infant mortality on the 'wet' soils was found to be 31.9% greater than on the 'dry' soils. The reason for this remains unexplained, though the authors noted that the wetter and perhaps colder air of the wet soil areas might result in babies or their mothers suffering from more colds and respiratory illnesses than otherwise would be the case. This study has proved controversial, and demonstrates the difficulties in establishing causative links between soils and health.

The importance of soils to human health has been undervalued until relatively recently, contributing to gaps in knowledge on the subject. Consequently, there still remains much to be done in the future. As examples, despite the problems noted above, the mapping and appraisal of health and soil data must continue as a priority since this can lead to the development of hypotheses that can be tested by further analytical studies. Many soils remain to be surveyed and characterised in detail, and even in developed countries some soils such as those associated with urban environments have been largely ignored to date. Soil contaminants constitute a known global problem, and more knowledge is required of them, their behaviour, and their pathways to humans. Remediation of contaminated and potentially hazardous soils has evolved into an important industry that will continue to be developed, particularly since brown field sites are increasingly being identified as locations for future human habitation. A number of developed countries have established lists of critical concentrations (or 'trigger concentrations') for the risk assessment of sites (CCME, 1997; ICRCL, 1987; VROM, 1991), though to date these have not always proved to be pragmatic or justified (Beckett, 1993). Environmental risk assessment of contaminated sites has matured into a coherent discipline in the USA, but still remains to be fully established as an academic discipline elsewhere (Ferguson, 1996).

Medical researchers need to be involved in further studies linking soils and health. For example, nutritionists are currently investigating Se in the British diet following concern that intake of this element is now seriously depleted. This has arisen since imports of wheat flour from North America have been reduced in favour of European wheat grown on soils of generally low Se content. Medical researchers also need to continue developing effective medicines. For example, potentially fatal diseases caused by the inhalation of airborne soil fungal spores may soon be prevented by new kinds of vaccines (Wuthrich et al., 2000). Furthermore, if proponents of the hygiene hypothesis are correct, soil mycobacterial derivatives may prove effective in the therapy of allergies and certain autoimmune conditions.

A key aspect for the future is that there is a real integration of professionals to produce a complete assessment of the problems that soils pose to humans. Such a multidisciplinary approach to the research needs to include not only those who call themselves soil scientists or biomedical researchers, but others such as agronomists, geochemists, pesticide and water quality researchers, planners, legislators and administrators. These professionals need to develop strategies that will cure or ideally prevent the health problems caused by soils. Some of the strategies will certainly be difficult to realise. For example, to meet the goal of long-term food productivity will require, in part, a major research effort for halting and reversing soil degradation (Syers, 1997). Even so, often soil/health problems once identified can be overcome relatively easily, as demonstrated by people at risk from a trace element deficiency disorder. Thus in populations with a low dietary intake of Se, the use of soil fertilisers, foliar sprays and supplements to humans of sodium selenite or yeast Se have all proved effective. It is important that the treatment with dietary supplements occurs early, and is supported by good health education. The latter is also a key that needs to be considered in the future. For example, podoconiosis can be prevented simply through the use of footwear that protects the skin of the foot from repeated, direct contact with the soil (Price, 1984). However, such advice can be difficult to get the patient to respond to, since they prefer to have medication. Finally, to acquire knowledge from multidisciplinary research, and to disseminate it to people in an understandable way, requires an infrastructure and finance that governments need to be responsive to.

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